

Triple trouble for XZ Tau: deep imaging with the Jansky Very Large Array

D. Forgan^{1*}, R.J. Ivison^{1,2}, B. Sibthorpe³, J.S. Greaves⁴, E. Ibar^{5,6}

¹*SUPA, Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh, EH9 3HJ, UK*

²*European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany*

³*SRON Netherlands Institute for Space Research, Landleven 12, NL-9747 AD Groningen, the Netherlands*

⁴*SUPA, School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews KY16 9SS, UK*

⁵*Instituto de Astrofísica. Facultad de Física. Pontificia Universidad Católica de Chile. Casilla 306, Santiago 22, Chile*

⁶*Instituto de Física y Astronomía. Universidad de Valparaíso. Avda. Gran Bretaña 1111. Valparaíso. Chile*

Accepted

ABSTRACT

We present new observations of the XZ Tau system made at high angular resolution (55 milliarcsec) with the Karl G. Jansky Very Large Array (VLA) at a wavelength of 7 mm. Observations of XZ Tau made with the VLA in 2004 appeared to show a triple-star system, with XZ Tau A resolved into two sources, XZ Tau A and XZ Tau C. The angular separation of XZ Tau A and C (0.09 arcsec) suggested a projected orbital separation of around 13 AU with a possible orbital period of around 40 yr. Our follow-up observations were obtained approximately 8 yr later, a fifth of this putative orbital period, and should therefore allow us to constrain the orbital parameters of XZ Tau C, and evaluate the possibility that a recent periastron passage of C coincided with the launch of extended optical outflows from XZ Tau A. Despite improved sensitivity and resolution, as compared with the 2004 observations, we find no evidence of XZ Tau C in our data. Components A and B are detected with a signal-to-noise ratio greater than ten; their orbital motions are consistent with previous studies of the system, although the emission from XZ Tau A appears to be weaker. Three possible interpretations are offered: either XZ Tau C is transiting XZ Tau A, which is broadly consistent with the periastron passage hypothesis, or the emission seen in 2004 was that of a transient, or XZ Tau C does not exist. A fourth interpretation, that XZ Tau C was ejected from the system, is dismissed due to the lack of angular momentum redistribution in the orbits of XZ Tau A and XZ Tau B that would result from such an event. Transients are rare but cannot be ruled out in a T Tauri system known to exhibit variable behaviour. Our observations are insufficient to distinguish between the remaining possibilities, at least not until we obtain further VLA observations at a sufficiently later time. A further non-detection would allow us to reject the transit hypothesis, and the periastron passage of XZ Tau C as agent of XZ Tau A's outflows.

Key words: methods: observational — radio continuum: stars — techniques: interferometric — (stars:) binaries (including multiple): close

1 INTRODUCTION

XZ Tau is a binary system composed of a T Tauri star, XZ Tau A, with a cool companion, XZ Tau B, separated by approximately 0.3 arcsec, at a distance of approximately 140 pc from Earth (Haas, Leinert & Zinnecker 1990; Kenyon, Dobrzycka & Hartmann 1994; Torres et al. 2009). Like many other T Tauri stars, XZ Tau A drives collimated jets and optical outflows (Mundt et al. 1990; Krist et al. 1997). *Hubble Space Telescope* imaging of these outflows shows nebular emission in the shape of an elongated bubble with expansion velocities of around

70 km s^{−1} (Krist et al. 1999). The substructure displayed by the bubble suggests its driver is episodic, with the cause attributed to a velocity pulse in the jet of XZ Tau A, triggered in the early 1980s (Krist et al. 2008). These previous studies, particularly that of Krist et al., explored the possibility that the periastron passage of XZ Tau B could have caused the outflows (cf. Forgan & Rice 2010). However, this would require an eccentric orbit, which is inconsistent with observations of the A/B system, which instead suggest a circular, face-on orbit. Also, the periastron passage of XZ Tau B would have occurred in the 1950s, too early to cause the outflow.

The periastron passage hypothesis was revived by more recent observations of the XZ Tau system using the Very Large Array (VLA) by Carrasco-González et al. (2009). Observations of the

* email:dhf@roe.ac.uk

7-mm continuum resolved XZ Tau A into two components, with the new component, XZ Tau C, separated by around 0.09 arcsec (13 AU). The non-detection of XZ Tau C in the optical waveband was suggestive of a stellar object heavily embedded in a dusty envelope or disk. While a single detection yielded no information on the orbit of component C around A, the existence of XZ Tau C increased the likelihood of a close approach to XZ Tau A, making it a potential trigger for the outflow.

Carrasco-González et al. (2009) speculate that if the orbit of XZ Tau C is circular, and the total system mass is $\approx 1 M_{\odot}$, then the orbital period of XZ Tau C should be around 40 yr. If the A/C system was close to apastron at the epoch of detection (2004), this would place XZ Tau C at periastron in the 1980s, as required, and a further ejection from XZ Tau A could be expected around 2020. However, the data available to the authors was insufficient to confirm orbital parameters, and as such this explanation for the outflows was tentative. Further observations of XZ Tau C at sufficiently later epochs would be required to either confirm or refute the periastron passage model for outflow generation.

To this end, we observed the XZ Tau system at high angular resolution, using the newly upgraded Karl G. Jansky VLA at 7 mm, to confirm the existence of XZ Tau C and constrain its orbital parameters. The time interval between our observations (2012) and the previous observations (2004) corresponds to approximately one fifth of the potential orbital period of XZ Tau C. These observations yield no detection of XZ Tau C, and the positions of XZ Tau A and B are consistent with the orbital solutions presented by previous studies. This Letter is composed as follows: we describe the observations taken in §2; we discuss the results in §3, and we summarise the work in §4.

2 OBSERVATIONS

Our Q-band observations of the XZ Tau system were obtained using the National Radio Astronomy Observatory's¹ VLA, deployed in its most extended configuration ('A'), during three days in 2012 October (project code 12B-133, 2012 October 6, 11, 13, pointing centre R.A. 04 31 40.072, Dec +18 13 57.18). Each 1-hr observing block was scheduled during a period of excellent phase stability, with low wind speed. Dual-circular-polarisation data with a total bandwidth of 2 GHz, comprising multiple 1-MHz channels centred at an observing frequency of 41 GHz (≈ 7 mm), were recorded every 1 s.

At the start of each observing block, the pointing accuracy of the antennas was refined using 3.6-cm continuum observations, just prior to observations of J0137+331 (3C 48, used to calibrate the flux density scale) and J0431+2037 (used alongside J0431+1731 to track the complex gains on a timescale of 5 min, and to correct for the bandpass response, and to test our likely astrometric accuracy). The positions of J0431+2037 and J0431+1731 are known to ≈ 10 and ≈ 2 milliarcsec, respectively, according to the NRAO Calibrator Manual.

Our data were edited using standard *AIPS* procedures and calibrated using a recipe designed for high-frequency radio observations, as described in detail by Ivison et al. (2013). The complex gains for our XZ Tau scans were calibrated using both J0431+2037

and J0431+1731. A calibrated J0431+2037 dataset was also produced, using only J0431+1731. Imaging of the calibrated *uv* visibilities was also accomplished via *AIPS*, using IMAGR, with 10-milliarcsec pixels. The position of J0431+2037 was found to be $\alpha = 04 : 31 : 03.76117 \pm 0.00002$, $\delta = +20 : 37 : 34.2652 \pm 0.0003$ (J2000), discrepant by 12 and 15 milliarcsec in R.A. and Dec. from values in the NRAO Calibrator Manual, so consistent with the expected uncertainties. The astrometric measurement error here, for a signal-to-noise ratio of ≈ 55 and a synthesised beam with full width at half maximum (FWHM) of ≈ 55 milliarcsec, is expected to be ≈ 1 milliarcsec (Ivison et al. 2007), so we are dominated by systematics and our ability to transfer phase information accurately from J0431+1731.

The three individual XZ Tau datasets produced self-consistent images. Combining the data and employing a natural weighting scheme yielded a 59×53 -milliarcsec (FWHM) synthesised beam, with a north-south major axis at position angle 177° , which was used to lightly clean the images; the resulting $1\text{-}\sigma$ noise level (at the pointing centre) was $23 \mu\text{Jy beam}^{-1}$.

3 RESULTS & DISCUSSION

The top-left panel of Fig. 1 shows our 7-mm continuum map of the XZ Tau system. As it was our goal to detect the positions of all three components to high precision, our observations resolve out extended emission from XZ Tau A or B. Table 1 shows the positions and flux densities of the two detected components, as derived from the 7-mm map. Note that while XZ Tau B has a similar flux density as was recorded by Carrasco-González et al. (2009), XZ Tau A has a flux density less than half than previously, despite subsequent improvements to the sensitivity of the instrumentation used.

If the two detected components in this map correspond to XZ Tau A (southern component) and XZ Tau B (northern component), then their orbital parameters should be consistent with the literature. We show the measured PA of the A–B binary in the top-right panel of Fig. 1. Our PA of 129.67 degrees is consistent with the orbital angular velocity measured in Carrasco-González et al. (2009) of $\Omega = -0.9 \pm 0.1$ degrees yr^{-1} , which we confirm by refitting the data with our extra point (and excluding the B–C data point from Carrasco-González et al. 2009).

The separation of the components is also similar to previous measurements at 0.282 arcsec. If the orbit is assumed to be circular, then the best-fit line corresponds to a separation of 0.296 ± 0.004 arcsec, or 41.4 AU at 140 pc. As a sanity check, the relative R.A. and Dec. (bottom-right panel of Fig. 1) can be fit with a circle of radius 41.5 AU at 140 pc, with an uncertainty in the fit of approximately 0.08 AU or 0.5 mas. The fit does not improve significantly if the projected orbit is allowed to be elliptical, so we conclude that the orbit of XZ Tau A and B is close to face-on and circular.

These observations provide strong evidence that the two components detected in the map do correspond to XZ Tau A and B. There is no detection of XZ Tau C, despite using the same facility as Carrasco-González et al. (2009), which has since been improved substantially; if XZ Tau C was present at the same flux density as previously recorded, our observations should have detected it with a signal-to-noise ratio of at least 3. Subsequent reductions using the CASA pipeline also did not detect a third component.

There are four possible interpretations of the data:

- (i) XZ Tau C was ejected from the system;

¹ This work is based on observations carried out with the VLA. The NRAO is a facility of the NSF operated under cooperative agreement by Associated Universities, Inc.

Table 1. Detected Components in the XZ Tau System

Component	Identifier	R.A.	Dec.	Flux Density (μ Jy)
N	XZ Tau B	04 31 40.0811 \pm 0.0002	18 13 56.890 \pm 0.002	343.0 \pm 48.5
S	XZ Tau A	04 31 40.0953 \pm 0.0001	18 13 56.712 \pm 0.002	528.2 \pm 55.5

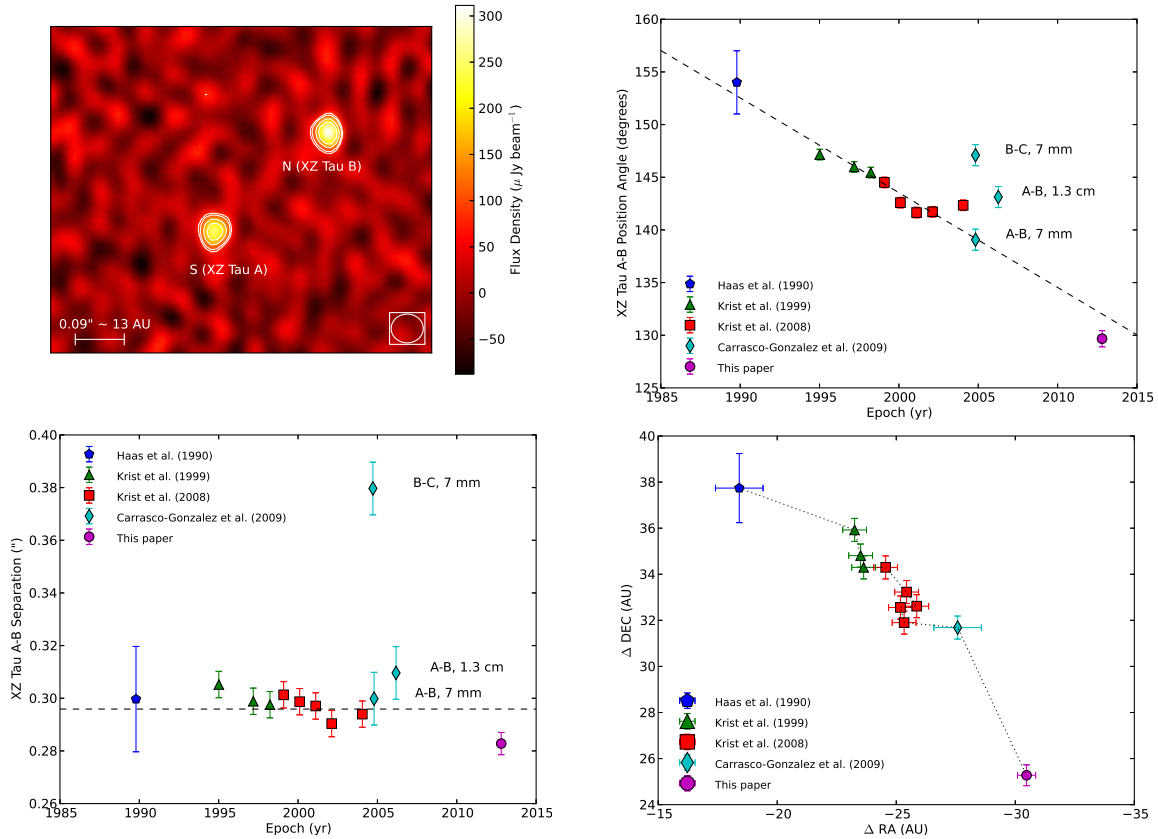


Figure 1. Top left: XZ Tau system, imaged at 7 mm using VLA. Contours are plotted for 80, 100, 150 and 200 μ Jy beam $^{-1}$. The beam silhouette plotted refers to the synthesised beam described in section 2, with FWHM of 59×53 -milliarcsec. Top right: change of position angle between XZ Tau A and B with epoch. Also plotted is the separation between XZ Tau B and XZ Tau C as calculated by Carrasco-González et al. (2009). The dashed line corresponds to a best-fit orbital angular velocity of -0.9 degrees yr $^{-1}$. Bottom left: projected angular separation of XZ Tau A and B with epoch. The dashed line corresponds to a best-fit horizontal line of 0.296 ± 0.002 arcsec. Bottom right: evolution of the R.A. and Dec. of XZ Tau B relative to XZ Tau A, measured in the projected spatial distance at 140 pc, as a function of time. The dashed line corresponds to the best-fit orbit, assuming a circular, face-on configuration, with radius of 41.5 AU.

(ii) the emission seen by Carrasco-González et al. was due to a transient;

(iii) XZ Tau C is currently transiting (or being eclipsed by) XZ Tau A, and cannot be resolved;

(iv) XZ Tau C does not exist, and its previous detection was an artefact of the data calibration and analysis.

We can quickly rule out the first possibility. No other sources that could correspond to an ejected XZ Tau C were detected. For XZ Tau C to leave the field of view (at 7mm, this is approximately 1.1 arcsec) would require proper motions around 0.14 arcsec per year, corresponding to a speed of around 95 kilometres per second on the sky. This is not an impossibly large velocity, but the orbits of XZ Tau A and B remain unperturbed, which is highly unlikely given the angular momentum redistribution an ejection would entail, as well as the typical recoil experienced by a bi-

nary when a third star is ejected (Monaghan 1976; Reipurth 2000; Reipurth & Mikkola 2012).

We cannot rule out emission from a transient, particularly not in a system known to exhibit variability. In general, young stellar objects display transient emission over the wavelength range probed by the VLA (see e.g. Dzib et al. 2013). Conversely, we note that extragalactic transient events are rare (e.g. Carilli, Ivison & Frail 2003; Frail et al. 2012; Mooley et al. 2013).

For XZ Tau C to have triggered the outflows from XZ Tau A at the appropriate epoch, Carrasco-González et al. (2009) assume that the orbit of XZ Tau C should be nearly circular ($e \approx 0.1$) and face-on, where they assume the total mass of A and C is approximately $1M_{\odot}$ and that XZ Tau C was at apastron during their observations (2004.8, with an apastron radius of approximately 13 AU). However, if the orbit is edge-on rather than face-on, an $e = 0.1$ or-

bit with the same apastron radius is approximately consistent with XZ Tau C being either in transit or in eclipse. If this interpretation is correct, then the periastron passage hypothesis may also be correct. However, transits of A by C remain possible with other selections of orbital parameters, and cannot be ruled out thanks to the non-detection reported here.

On the other hand, this interpretation would require XZ Tau C to orbit almost perpendicular to the A–B binary plane, leaving it vulnerable to strong perturbations from the Kozai-Lidov mechanism (Kozai 1962; Lidov 1962), generating significant coupled oscillations in the star’s eccentricity and inclination (Naoz et al. 2013). Given that the oscillation timescale is several orders of magnitude larger than the interval between epochs of observation, this possibility cannot be ruled out.

This leaves us with the final interpretation – that the previous detection of XZ Tau C was erroneous. This is consistent with the non-detection of XZ Tau C at optical wavelengths. While it is true that XZ Tau C could have been a highly embedded star, as Carrasco-González et al. (2009) suggest, a non-detection at 7 mm is not consistent with this interpretation. Observations at a sufficiently later epoch are required to decide which of our interpretations is most likely.

4 CONCLUSIONS

We report observations of the XZ Tau system, recently observed to possess a third component, XZ Tau C (Carrasco-González et al. 2009). This third component had been proposed as a potential driver for the outflows generated by XZ Tau A, which could have been generated by a periastron passage of this new object in the 1980s. Our new observations were made using the VLA in its most extended configuration, after a period of roughly one fifth of the object’s assumed orbital period, and can thereby constrain the orbit of XZ Tau C and test the periastron passage theory.

However, our observations yield no detection of XZ Tau C. XZ Tau A and B are both detected with a high degree of confidence, with positions and orbits consistent with those described in the literature.

Three potential interpretations of the data are possible. Of these, the most prosaic is that XZ Tau C does not exist, and was an artefact of reducing interferometric data, which is consistent with its non-detection in the optical. Alternatively, XZ Tau C may have been caught whilst transiting XZ Tau A, which is consistent with the orbital requirements for XZ Tau C to trigger outflows at periastron passage. This second interpretation would require the hierarchical triple to possess a large mutual inclination, and hence be dynamically unstable, but on timescales that are sufficiently long to remain consistent with the observations. Finally, we cannot rule out the possibility of a transient event local to this T Tauri system, a system known to be variable. To distinguish between these potential interpretations, determining the nature of XZ Tau C, requires a very brief, future observation using the VLA in A configuration. If the transit hypothesis is true, future observations should be able to detect XZ Tau C once it has moved away from XZ Tau A. If observations at this time fail to detect XZ Tau C, this would be sufficient to reject it as a cause of outflows being generated by XZ Tau A.

ACKNOWLEDGMENTS

DF gratefully acknowledges support from STFC grant ST/J001422/1. RJI acknowledges support in the form of ERC Advanced Investigator programme, COSMICISM. EI acknowledges funding from CONICYT/FONDECYT postdoctoral project N°:3130504. The authors thank Claire Chandler for reductions made using the CASA pipeline.

REFERENCES

- Carilli C. L., Ivison R. J., Frail D. A., 2003, *ApJ*, 590, 192
- Carrasco-González C., Rodríguez L. F., Anglada G., Curiel S., 2009, *ApJ*, 693, L86
- Dzib S. A. et al., 2013, *The Astrophysical Journal*, 775, 63
- Forgan D. H., Rice K., 2010, *MNRAS*, 402, 1349
- Frail D. A., Kulkarni S. R., Ofek E. O., Bower G. C., Nakar E., 2012, *ApJ*, 747, 70
- Haas M., Leinert C., Zinnecker H., 1990, *A&A*, 230, L1
- Ivison R. J. et al., 2007, *Monthly Notices of the Royal Astronomical Society*, 380, 199
- Ivison R. J. et al., 2013, *The Astrophysical Journal*, 772, 137
- Kenyon S. J., Dobrzycka D., Hartmann L., 1994, *The Astronomical Journal*, 108, 1872
- Kozai Y., 1962, *The Astronomical Journal*, 67, 591
- Krist J. E. et al., 1997, *ApJ*, 481, 447
- Krist J. E. et al., 1999, *ApJ*, 515, L35
- Krist J. E., Stapelfeldt K. R., Hester J. J., Healy K., Dwyer S. J., Gardner C. L., 2008, *The Astronomical Journal*, 136, 1980
- Lidov M., 1962, *Planetary and Space Science*, 9, 719
- Monaghan J. J., 1976, *MNRAS*, 177, 583
- Mooley K. P., Frail D. A., Ofek E. O., Miller N. A., Kulkarni S. R., Horesh A., 2013, *ApJ*, 768, 165
- Mundt R., Buehrke T., Solf J., Ray T. P., Raga A. C., 1990, *A&A*, 232, 37
- Naoz S., Farr W. M., Lithwick Y., Rasio F. A., Teyssandier J., 2013, *MNRAS*, 431, 2155
- Reipurth B., 2000, *The Astronomical Journal*, 120, 3177
- Reipurth B., Mikkola S., 2012, *Nature*, 492, 221
- Torres R. M., Loinard L., Mioduszewski A. J., Rodríguez L. F., 2009, *ApJ*, 698, 242